Conquer Chiari Research Center

The University of Akron

Strain on the Brain: Biomechanics of Chiari Malformation

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Cine-DENSE MRI
Displacement Encoded Stimulation Echo

Biomechanics

The scientific study of the role of **mechanics** in biological systems.

The American Heritage® Science Dictionary

Mechanics

The branch of physics concerned with the relationships between matter, force, and energy, especially as they affect the **motion of objects**.

The American Heritage® Science Dictionary

Motion

versus

Strain

http://www.hilariousgifs.com/

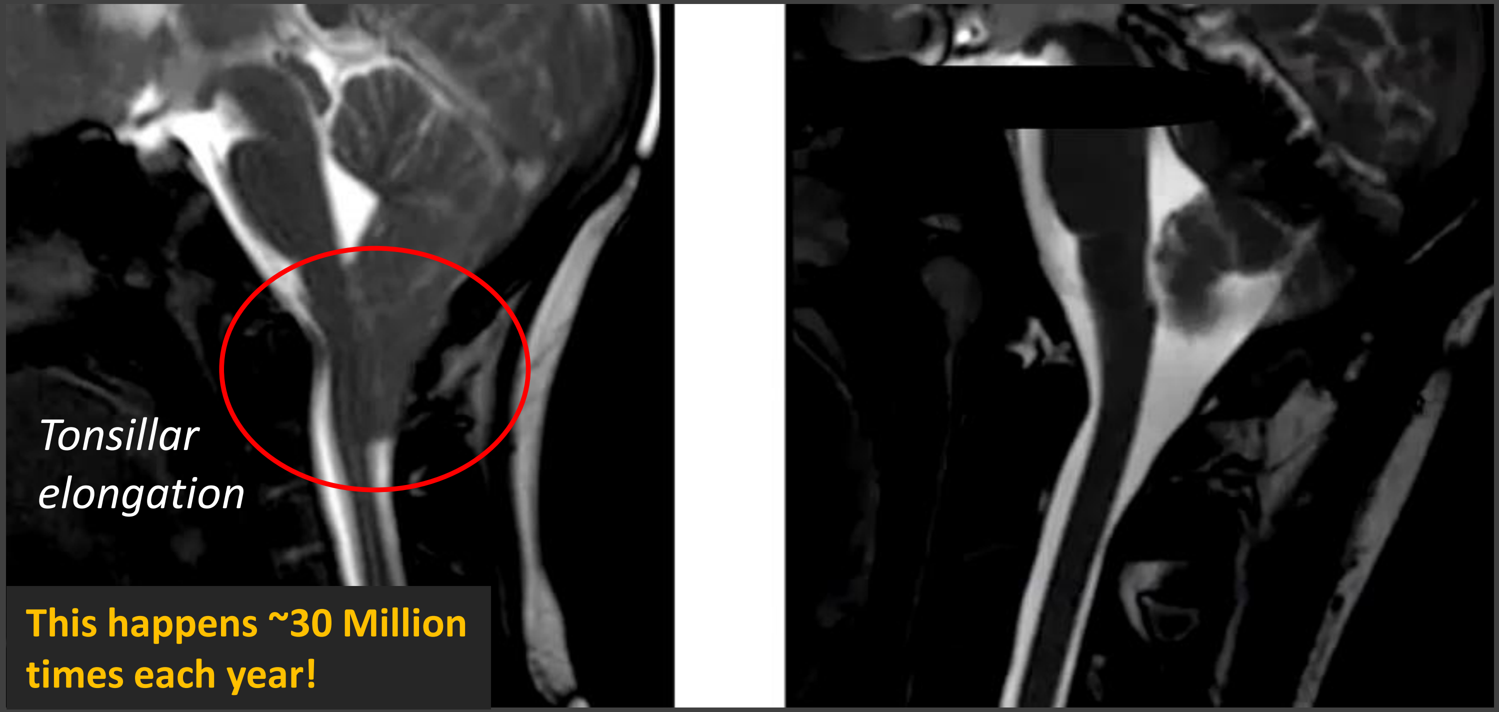
Motion versus Strain

Softer materials strain easier.

Brain motion in Chiari malformation

Chiari malformation patient

Healthy subject



Goal: To determine the impact of the increased motion on neural tissue strain.

Videos courtesy of Alexander Bunck, M.D.

MR images captured **by K-t BLAST technique** on Siemens Magnetom scanner

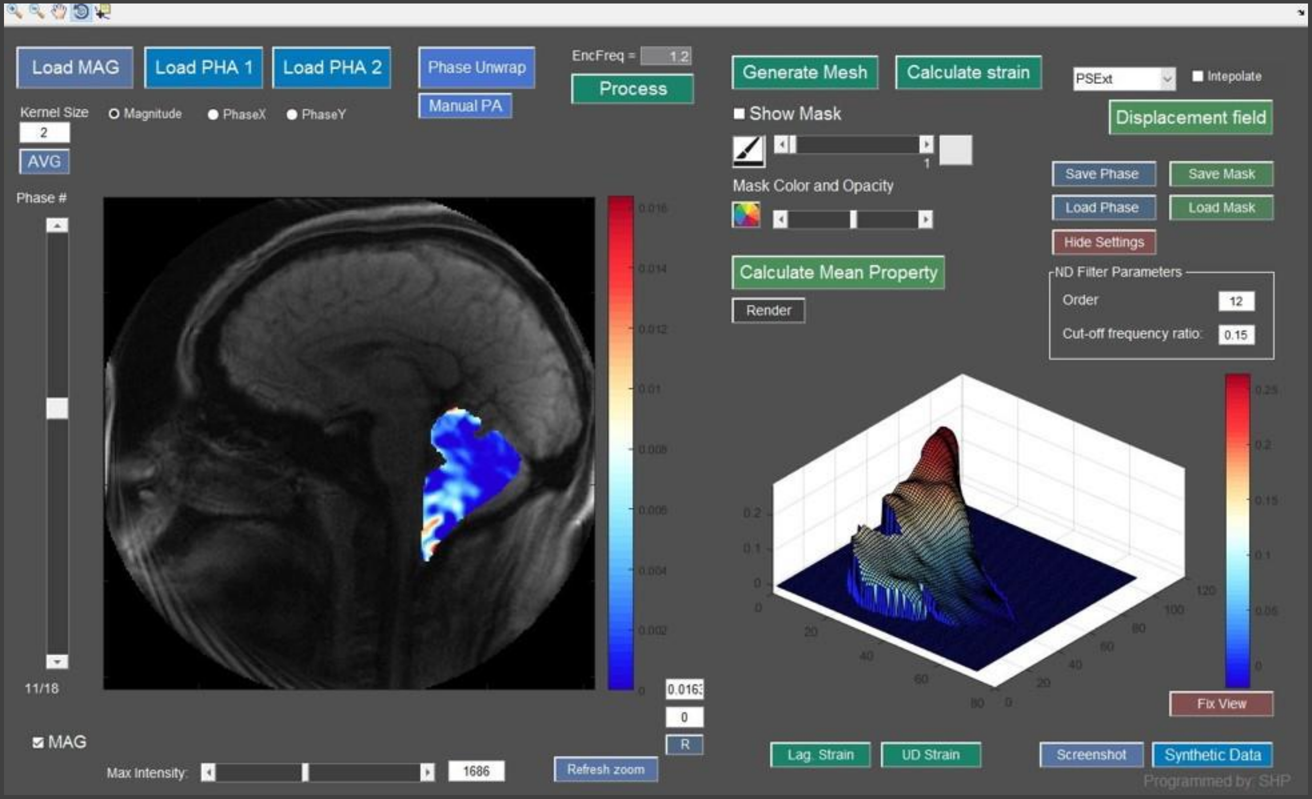
DENSE processing

Displacement Encoded Stimulation Echo sequence settings

- 1.5-3.0T whole body scanner
- four-channel head coil + single channel neck coil
- FOV: 256*256
- Resolution: 1.4×1.4×7 mm, temp: 30-34 ms
- TE: 1.9 ms. Flip angle: 15°

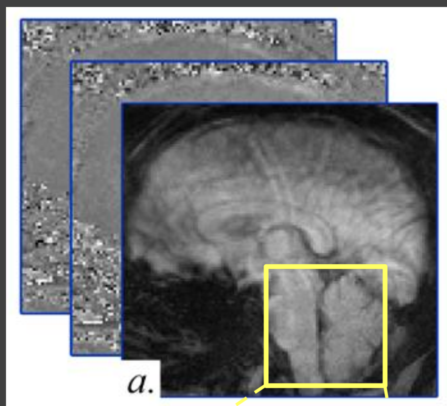
DENSEPro

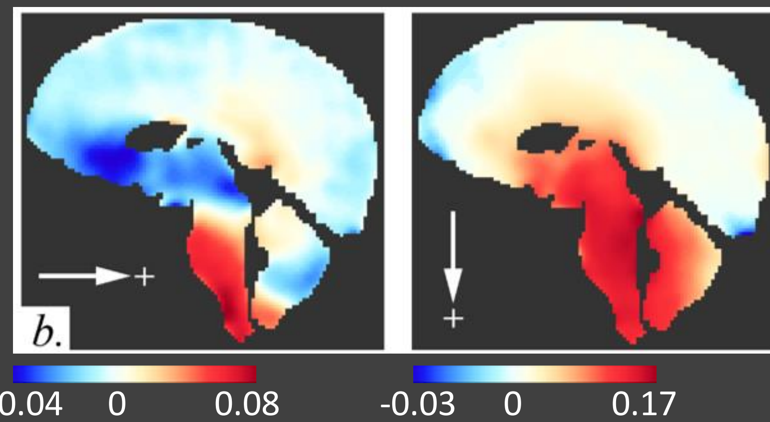
- DENSE and PCMRI post-processing software.

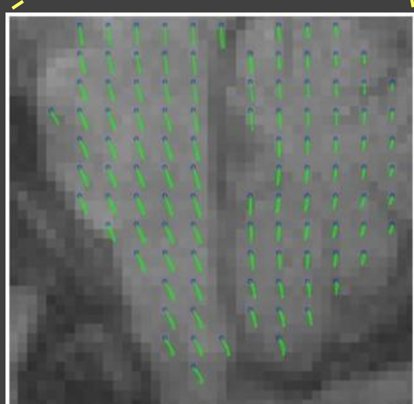


Displacement and strain calculations

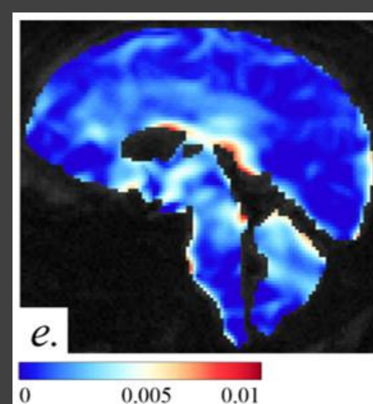
Eulerian displacement (mm)







Lagrangian tracks



Compression strain

$$\begin{bmatrix} x_1^1 & x_1^2 & \dots & x_1^n \\ x_2^1 & x_2^2 & \dots & x_2^n \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} & p_1 \\ F_{21} & F_{22} & p_2 \end{bmatrix} \begin{bmatrix} X_1^1 & X_1^2 & \dots & X_1^n \\ X_2^1 & X_2^2 & \dots & X_2^n \\ 1 & 1 & \dots & 1 \end{bmatrix}$$

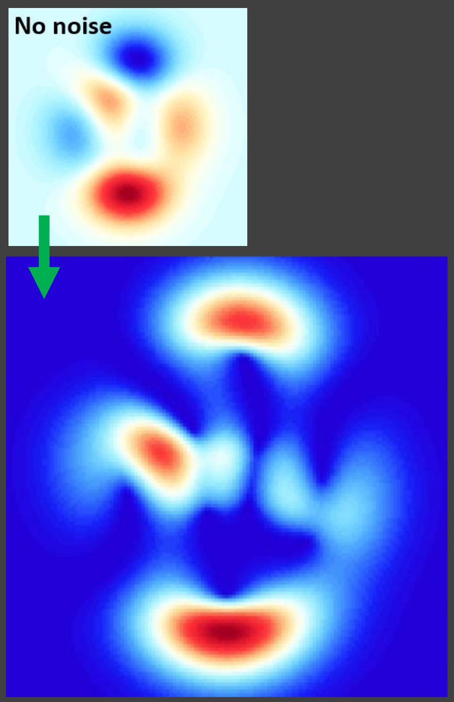
X: un-deformed configuration

x: deformed configuration

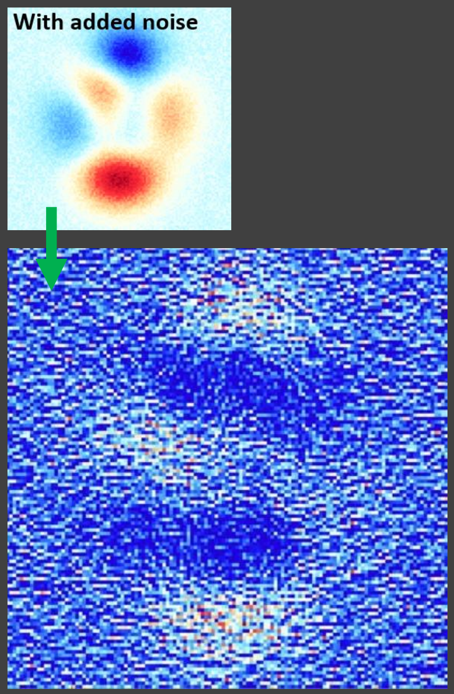
Green-Lagrange strain tensor: $\boldsymbol{E} = \mathbf{1/2}(\boldsymbol{FTF} - \boldsymbol{I})$

Post processing - random noise

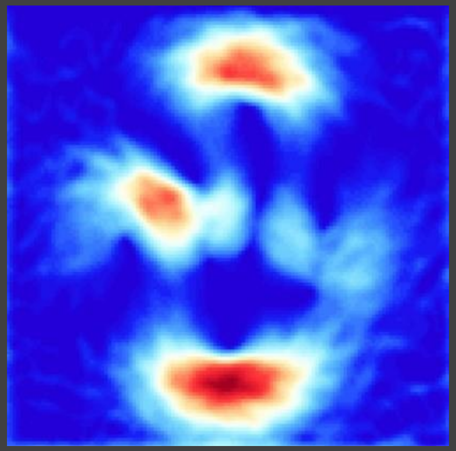
Strain field from synthetic displacement data:



Reference
(from synthetic displacement data)



Simulated with noise
(from synthetic displacement data + noise)



Noise-filtered
(from noise-filtered displacement)

Compression strain (%)

Healthy vs Chiari - Displacement

$N_{Healthy} = 6$, $N_{Chiari} = 8$

Mean displacement @ peak systole:

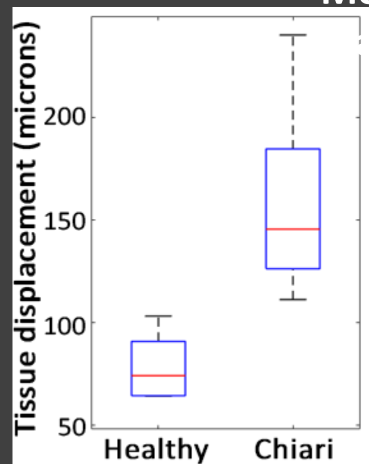
- **Cerebellum: 201%** increase

  (157.9 ± 43.8 vs 78.6 ± 16.5, p = 0.0007)

- **Brain stem: 139%** increase

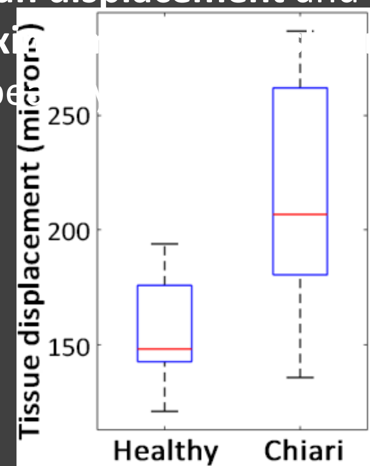
  (215.0 ± 53.3 vs 154.9 ± 26.1, p = 0.029)

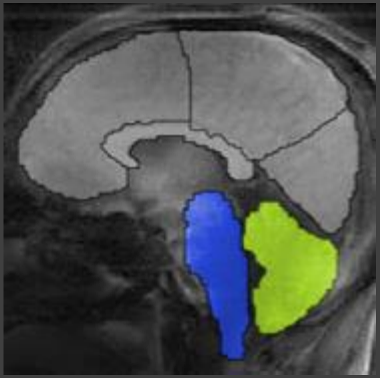
Cerebellum



Brain stem

Mean displacement and





- Displacement values and trend agreed with the literature[1,2].
- Typical peak displacement: **0.07 - 0.3 mm** compared to **4 - 8 mm** as reported for myocardium.

1. *Cousins J, Haughton V, AJNR Am. J. Neuroradiol. 30:1587–1588 (2009).*
2. *Enzmann DR, Pelc NJ, Radiology 185:653–660, (1992).*

Motion

versus

Strain

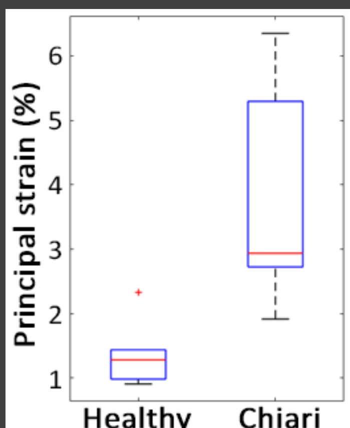
http://www.hilariousgifs.com/

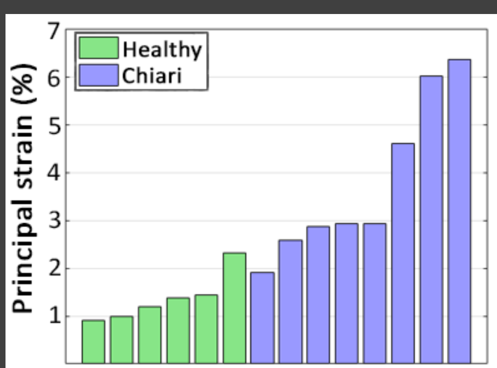
Healthy vs Chiari - Strain

Maximal compression strain @ peak systole:

- **Cerebellum: 292%** increase

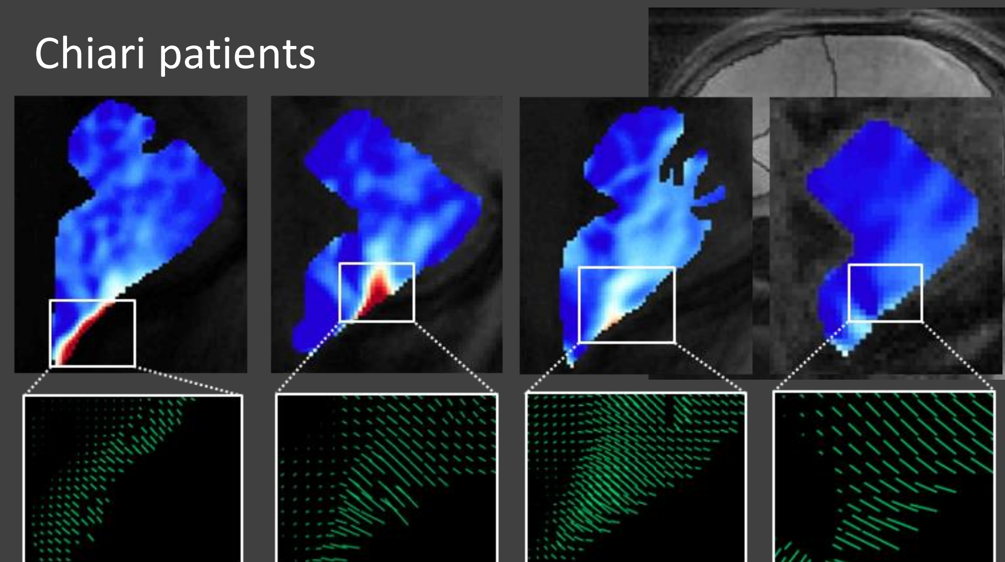
(3.8± 1.7 vs 1.3 ± 0.5, p = 0.001)



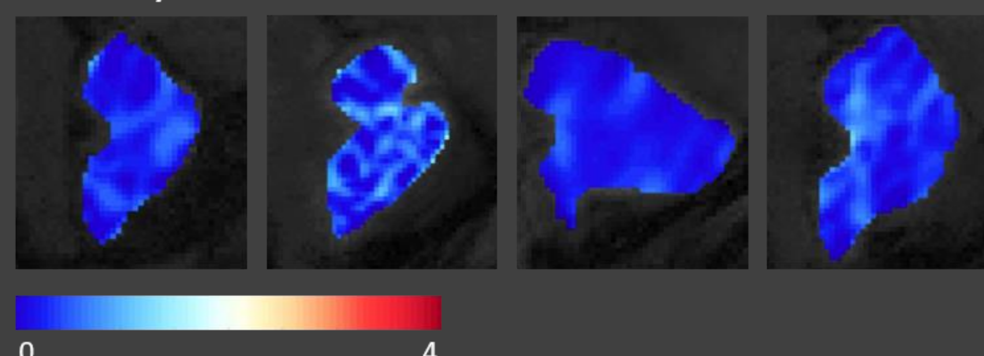


- Principal compression strain (%)

Chiari patients

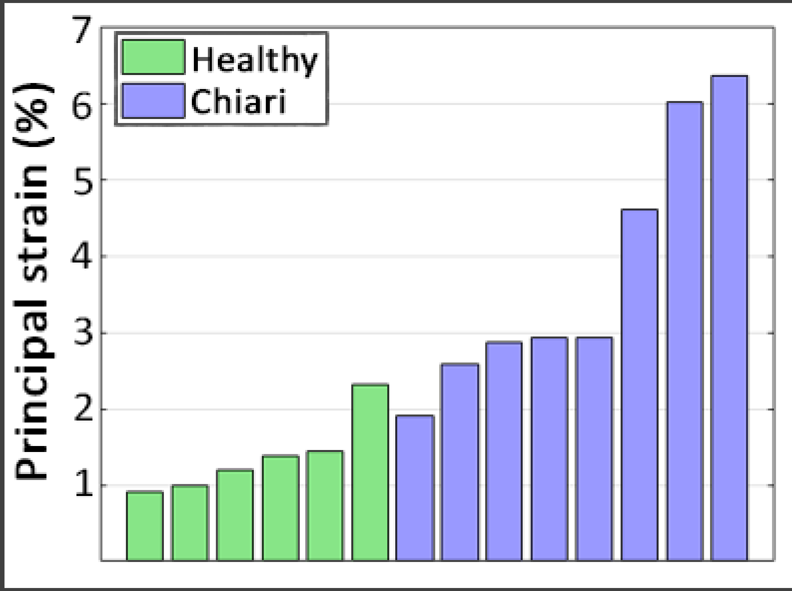


Healthy controls:



Healthy vs Chiari - Strain

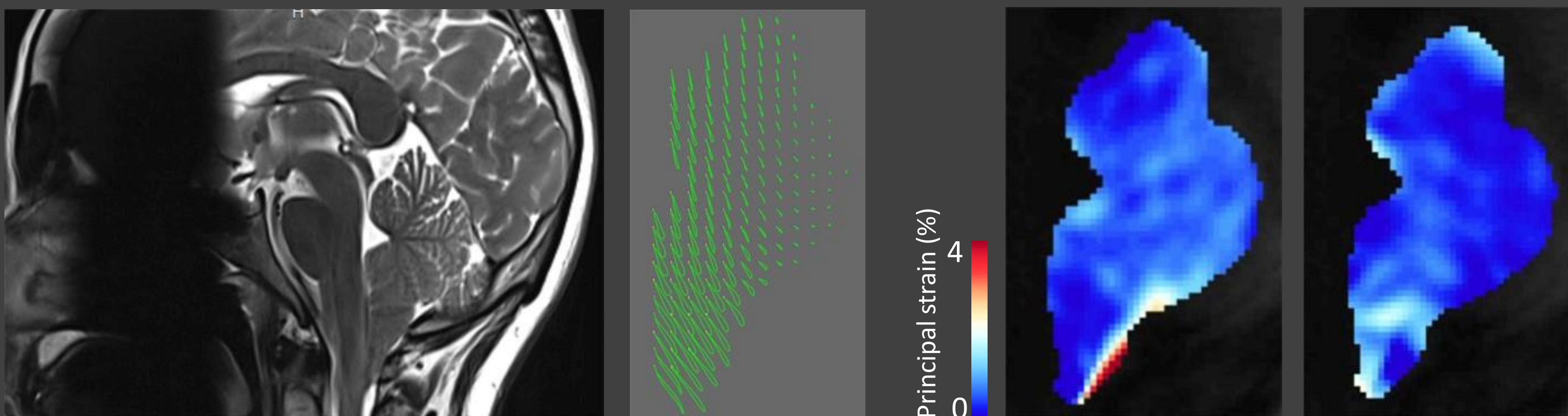
- Typical peak principal strains: 1 - 6% compared to **30 – 50%** as reported for myocardium.
- 20 - 30% maximal principal strain → Diffuse axonal injury[1].
- 10% maximal principal strain → enough to cause reversible injury to the axons (happens in concussion)[2].



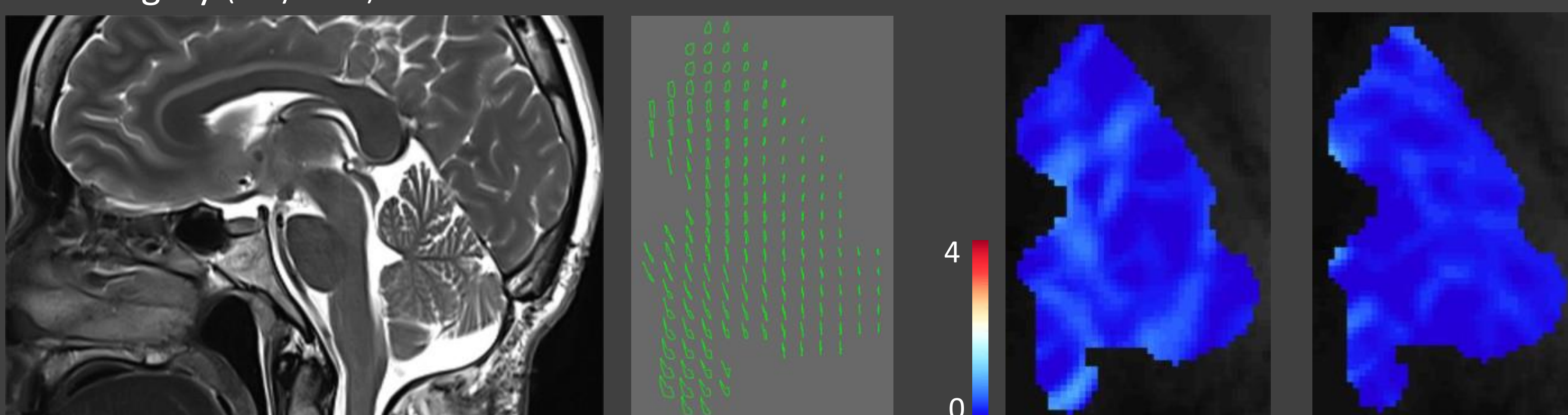
1. *Thibault L. E.. in Proceedings of the IRCOBI Conference, Eindhoven p. 3–252, (1993).*
2. *Morrison B 3rd, Cater HL, Wang CC, Thomas FC, Hung CT, Ateshian GA, Sundstrom LE Stapp Car Crash J., 47:93-105 (2003).*

Pre vs post surgery (preliminary results)

Pre-surgery (Jan 2017) | Motion tracks | - Compression | Extension



Post-surgery (May 2017)



Take-home Messages

- Cine-DENSE MRI is feasible for measuring displacement and strain of brain tissues.
- Compression tissue strain on cerebellum was significantly greater in Chiari patients compared to controls.

Open Questions

- Are the increased strains in Chiari patients (~4 to 7%) enough to cause injuries over time?
- Are the increased strains correlated with symptoms?
- Can the strain analysis be used as a biomarker for evaluating the severity of Chiari and help to predict the surgery outcome, in terms of symptoms relieve ... ?

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Regional Quantification of Brain Tissue Strain Using Displacement-Encoding With Stimulated Echoes Magnetic Resonance Imaging

Intrinsic cardiac-induced deformation of brain tissue is thought to be important in the pathophysiology of various neurological disorders. In this study, we evaluated the feasibility of utilizing displacement encoding with stimulated echoes (DENSE) magnetic resonance imaging (MRI) to quantify two-dimensional (2D) neural tissue strain using cardiac-driven brain pulsations. We examined eight adult healthy volunteers with an electrocardiogram-gated spiral DENSE sequence performed at the midsagittal plane on a 3 Tesla MRI scanner. Displacement, pixel-wise trajectories, and principal strains were determined in seven regions of interest (ROI): the brain stem, cerebellum, corpus callosum, and four cerebral lobes. Quantification of small neural tissue motion and strain along with their spatial and temporal variations in different brain regions was found to be feasible using DENSE. The medial and inferior brain structures (brain stem, cerebellum, and corpus callosum) had significantly larger motion and strain compared to structures located more peripherally. The brain stem had the largest peak mean displacement (PMD) (187 $\pm$ 50 μm, mean $\pm$ SD). The largest mean principal strains in compression and extension were observed in the brain stem (0.38 $\pm$ 0.08%) and the corpus callosum (0.37 $\pm$ 0.08%), respectively. Measured values in percent strain were altered by as much as 0.1 between repeated scans. This study showed that DENSE can quantify regional variations in brain tissue motion and strain and has the potential to be utilized as a tool to evaluate the changes in brain tissue dynamics resulting from alterations in biomechanical stresses and tissue properties. [DOI: 10.1115/1.4040227]

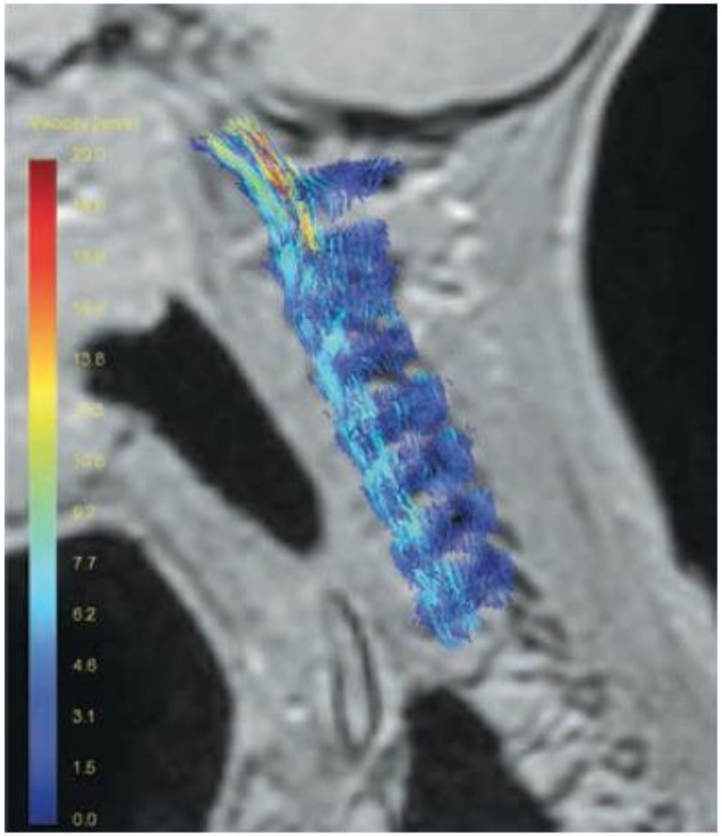

Figure 2a. 3-D measurement of CSF flow velocities by 4-D phase-contrast MRI[4] in a 5-year-old Chiari patient with mild tonsillar descent, showing regions of elevated CSF flow velocities on the anterior side of the spinal cord from the pontine cistern (image courtesy of Alexander Bunck, MD).

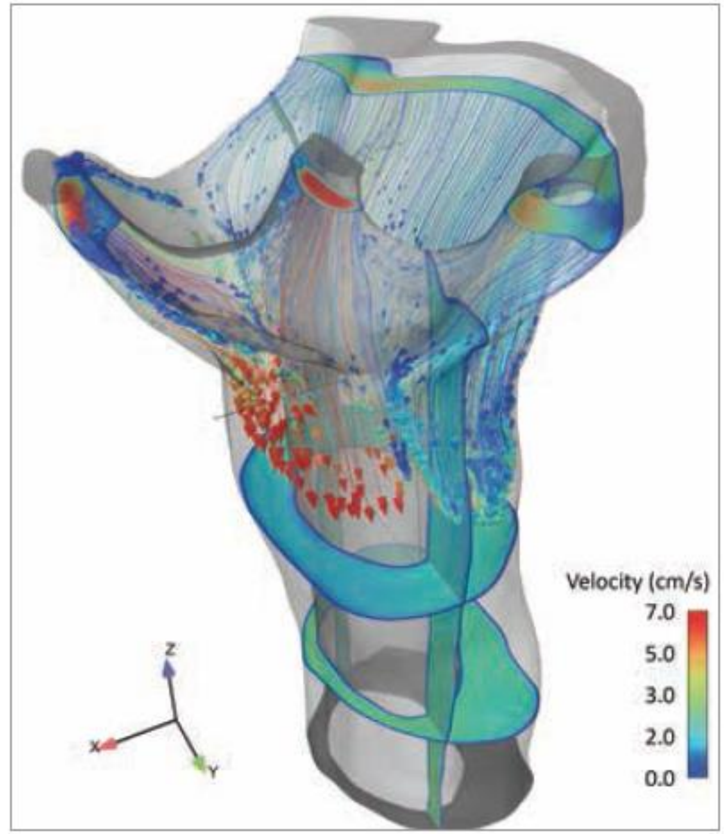

Figure 2b. Subject-specific computational fluid dynamics simulation of CSF motion based on in vivo MRI measurements from an adult-age Chiari patient with mild tonsillar descent below the foramen magnum[7] (figure left = posterior CSF space, right = anterior; arrows show direction and magnitude of velocity streamlines).

Acknowledgment

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